Relationship Between Texture and Electromigration Lifetime in Sputtered Al-1% Si Thin Films

ANN N. CAMPBELL and RUSSELL E. MIKAWA
Sandia National Laboratories, Department 2275, Albuquerque, NM 87185-5800
DAVID B. KNORR
Rensselaer Polytechnic Institute, Materials Engineering Department, Troy, NY 12180-3590

The relationship among the grain structure, texture, and electromigration lifetime of four Al-1% silicon metallizations produced under similar sputtering conditions was explored. The grain sizes and distributions were similar and the grain structure was near-bamboo for all metallizations. All metallizations exhibited a near-(111) fiber texture, as determined by the pole figure technique. Differences in electromigration behavior were noted. Three of the metallizations exhibited a bimodal failure distribution while the fourth was monomodal and had the longest electromigration lifetime. The electromigration lifetime was directly related to the strength of the (111) fiber texture in the metallization as anticipated. However, whereas the grain size distribution has an effect on the electromigration lifetime when metallization lines are several grains wide, the electromigration lifetime of these near-bamboo metallizations appeared independent of the grain structure. It was also observed that a number of failures occurred in the 8 μm interconnect supplying the 5 μm wide test lines. This apparently reflects an increased susceptibility of the wider interconnect lines to electromigration damage.

Key words: Bimodal grain size distribution, electromigration lifetime, fiber texture, grain size, metallization

INTRODUCTION

The microstructure of thin film interconnects is of vital importance to their reliability; for a given applied stress (temperature and current density), microstructure can have a dramatic effect on the median time to failure (MTTF) in an electromigration experiment.1-4 Because of the high potential payoff in terms of improved metallization reliability, a considerable amount of work has been performed to understand the relationship between film microstructure and electromigration lifetime. The microstructural parameters which have been found to be important include grain size, grain size distribution, texture, and the relationship between grain size and line width.1-5 In the present study, the relative importance of these microstructural parameters in determining the electromigration lifetime of Al-1% silicon metallizations with near-bamboo grain structure is explored.

Since electromigration in thin films occurs primarily by grain boundary diffusion, reducing the grain boundary area (i.e. increasing the grain size) generally leads to a reduction in the available paths for diffusion and hence to a reduced electromigration rate. The early work of Attardo and Rosenberg4 showed that the MTTF in an electromigration experiment increased and the deviation in time to failure (DTTF) decreased as the metallization grain size increased. In the limit that the grains are considerably larger than the line width, a bamboo structure, characterized by grain boundaries which are perpendicular to the line length and span the entire line width, develops during annealing of the metallization after patterning. In that case, atomic transport along grain boundaries no longer contributes to the electromigration process, which proceeds at the slower lattice diffusion-limited rate.1

Electromigration damage results when there is an unequal flux of atoms (or vacancies) into and out of a region, which leads to voiding or to the accumulation of excess material. Locations where this occurs are
termed flux divergence sites. Grain boundary triple points (locations at which three grain boundaries intersect) often serve as sites where there is an abrupt change in grain size or where grain boundaries of widely differing mobilities (due to orientation or type of boundary) intersect.\textsuperscript{1,4} The grain size distribution is also important in interconnect reliability because a broad grain size distribution can increase the number of potential flux divergence sites and hence reduce the MTTF. For example, a large divergence in the grain size distribution greatly increases the probability of finding non-bamboo grains embedded in a bamboo grain structure, increasing the probability of early failure. As another example, Cho and Thompson have shown that a severely bimodal grain size distribution has a disastrous effect on electromigration lifetime.\textsuperscript{2}

The texture of aluminum thin film metallizations has a pronounced effect on their electromigration behavior. It has long been recognized that a strong (111) texture is associated with improved electromigration lifetime.\textsuperscript{2-4} This is true because grain boundary diffusivity is a strong function of grain boundary orientation,\textsuperscript{6} which is in turn determined by the grain orientation, or texture. An empirical relationship among texture, grain size, grain size distribution, and MTTF was described by Vaidya et al.\textsuperscript{2,3}

\[
\text{MTTF} \sim d/\sigma^2 \log \left( \frac{I_{111}}{I_{200}} \right)^3 \tag{1}
\]

In this expression, MTTF increases linearly with grain size, \(d\), and is inversely proportional to the variance in the lognormal grain size distribution, \(\sigma^2\). The “texture factor” is the term \(\log \left( \frac{I_{111}}{I_{200}} \right)^3\), where \(I_{111}\) and \(I_{200}\) refer to the integrated peak intensities for the (111) and (200) reflections in a \(\theta/2\theta\) (Bragg-Brentano geometry) diffractometer scan. Equation 1 reflects the considerable improvement in MTTF associated with a strong (111) texture.

Aluminum thin films typically have a (111) fiber texture, which means that the texture exhibits axial symmetry about some direction, typically the sample normal direction.\textsuperscript{7} Two parameters are used to represent the (111) fiber texture: \(\omega\), which describes the width of the (111) distribution, and \(V_{\text{random}}\), which is the volume fraction of randomly oriented grains in the sample. Recently Knorr et al. suggested that, since the (200) reflections are randomly distributed for a (111) fiber texture, the texture factor can be equivalently written:

\[
\log \left( \frac{I_{111}}{I_{200}} \right)^3 = \log \left( \frac{V_{\text{random}}}{V_{\text{random}}} \right)^3 \tag{2}
\]

where \(V_{\text{random}}\) is the volume fraction of the (111) texture component determined from a pole figure measurement of texture.\textsuperscript{11,12} The experiments of Knorr et al. found reasonably good agreement between the two expressions for the texture factor.

In addition to these purely microstructural factors, the relationship between the metallization grain size, \(d\), and line width, \(w\), is also of importance. The effect of line width on failure statistics has been extensively studied.\textsuperscript{13,14} and the term \(w/d\) has emerged as the appropriate scaling parameter for the effect of line width on electromigration behavior.\textsuperscript{5} Four regimes of \(w/d\) can be described:

1. **Polycrystalline lines**: \(w/d\) is large, and the lines are at least several grains wide at all locations. This typically gives rise to a monomodal failure distribution with low MTTF and low DTTF.
2. **Near-Bamboo**: \(w/d = 1\), and some grains with diameters less than the line width are present. The failure distribution may be bimodal, and DTTF is generally high.\textsuperscript{5}
3. **Bimodal**: A mixture of large grains (\(w/d < 1\)) and small grains (\(w/d > 1\)) is present. MTTF and DTTF are low when the volume fraction of large grains is less than 90%. As the volume fraction of large grains approaches 100%, the failure distribution becomes bimodal. Deviation in time to failure is higher for the late failures than the early failures.\textsuperscript{6}
4. **Bamboo**: \(w/d < 1\). In this case, all grain boundaries span the line width. Median time to failure is very high and DTTF is low.

The early studies of microstructural effects on electromigration behavior\textsuperscript{2-4} fall into the first category. As the technology has advanced and line widths have narrowed, metallizations which fall into \(w/d\) categories (2)–(4) have become increasingly prevalent. A variety of reasons for the bimodal failure distributions referred to in categories (2) and (3) have been advanced.\textsuperscript{6,7} In general, this situation arises when two distinct types of failure sites are present. For example, it has been suggested that different atomic mobilities associated with “random” and “oriented” grain boundaries in weakly textured, near-bamboo aluminum thin films give rise to a bimodal failure distribution.\textsuperscript{7} As a second example, a bimodal failure distribution was observed in metallizations with a bimodal grain size distribution when the fraction of large grains approached 100%.\textsuperscript{6} The early failures were attributed to flux divergence sites associated with small grains. The later failures were thought to occur at bamboo grain boundaries when the small grains either did not occur in a given test line, or the corresponding grain boundaries were not activated as flux divergence sites.

Thus, several factors contribute to the electromigration lifetime of aluminum thin film metallizations. In this paper, the differences in electromigration lifetime among a set of samples with similar grain size and structure (near-bamboo) are discussed in terms of subtle differences in texture and grain size distribution.

**EXPERIMENTAL**

Thin films of composition Al-1% silicon were produced by magnetron sputter deposition at 250°C and were used in the fabrication of test wafers for the evaluation of a new metallization process. Films of